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Key Points:

- Low velocities in the Gulf upper mantle are interpreted as partial melting
- Partial melting under the Guaymas Basin and off axis of the other rift basins
- Lower crustal flow assisted by heat source in N Gulf near mantle upwelling

Supporting Information:

- Text S1 and Figures S1 to S3

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Rayleigh wave dispersion measurements reveal low-velocity zones beneath the new crust in the Gulf of California

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Abstract Rayleigh wave tomography provides images of the shallow mantle shear wave velocity structure beneath the Gulf of California. Low-velocity zones (LVZs) are found on axis between 26 and 50 km depth beneath the Guaymas Basin but mostly off axis under the other rift basins, with the largest feature underlying the Ballenas Transform Fault. We interpret the broadly distributed LVZs as regions of partial melting in a solid mantle matrix. The pathway for melt migration and focusing is more complex than an axis-centered source aligned above a deeper region of mantle melt and likely reflects the magmatic evolution of rift segments. We also consider the existence of solid lower continental crust in the Gulf north of the Guaymas Basin, where the association of the LVZs with asthenospheric upwelling suggests lateral flow assisted by a heat source. These results provide key constraints for numerical models of mantle upwelling and melt focusing in this young oblique rift.

1. Introduction

Mantle depletion, asthenospheric upwelling, and an on-axis or off-axis magma supply are thought to influence the intensity of generation of new oceanic crust and the segmentation of rifts [e.g., *Toomey et al.*, 2007]. Shear wave tomography of the mantle beneath the Gulf of California shows large well-defined regions of convective upwelling beneath the Wagner, Delfin, and Guaymas Basins [*Wang et al.*, 2009] and beneath the Ballenas Transform Fault (BTF), and the Alarcon and Pescadero Basins [*Di Luccio et al.*, 2014] (Figure 1). Both studies show skewed mantle upwelling relative to sites of new crustal accretion indicating a complex system of magma supply from the asthenospheric mantle upward to the rift basins.

The complex pattern of mantle convection is also expressed in the anisotropic fabric beneath the Gulf. Shear wave splitting measurements at high [Obrebski et al., 2006; van Benthem et al., 2008] and low frequencies [Long, 2010] show broadly consistent results. The influence of present-day flow on the anisotropic fabric of the underlying mantle can be grouped into three categories, horizontal return flow away from the upwelling in the northern portion of the study region (NE70–NE72 in Figure 1), near-vertical mantle upwelling or nearly transform parallel flow in central Baja California (NE74–NE77), and more complex or insufficient data south of 25°N [Long, 2010; Obrebski et al., 2006; van Benthem et al., 2008]. The overall pattern reveals complex upper mantle anisotropy with a considerable degree of both lateral and vertical heterogeneity, which appears to be controlled by localized processes like upwelling associated with partial melting [Long, 2010].

Despite the rapid localization of the Pacific-North America plate boundary in this region ~6 Ma [Oskin et al., 2001] considerable variations in the evolution of rifting and transition to seafloor spreading have also been identified with no systematic along-strike pattern. From north to south, the crust ranges from ~15 km thick in the Delfin Basin [Gonzalez-Fernandez et al., 2005], which lacks evidence for seafloor spreading, to new ~6 km thick oceanic crust in the Alarcon Basin [Lizarralde et al., 2007] (Figure 1). However, the largest amount of oceanic crust and lithospheric rupture at ~6 Ma is found in the central Gulf in the Guaymas Basin, where the thickness of new oceanic crust is >7 km and the width of new igneous crust is ~280 km [Lizarralde et al., 2007]. To explain these differences, Lizarralde et al. [2007] proposed that it was not easy to melt the mantle beneath the Farallon, Pescadero, and Alarcon Basins by decompression melting since the mantle had been depleted during the Early Miocene ignimbrite flare-up [Ferrari et al., 2007]. As a result, these basins were magma poor at breakup. In contrast, the Guaymas Basin was magma rich at breakup due to its distal location relative to the regions of early mantle depletion, with the thermal blanketing effect of the

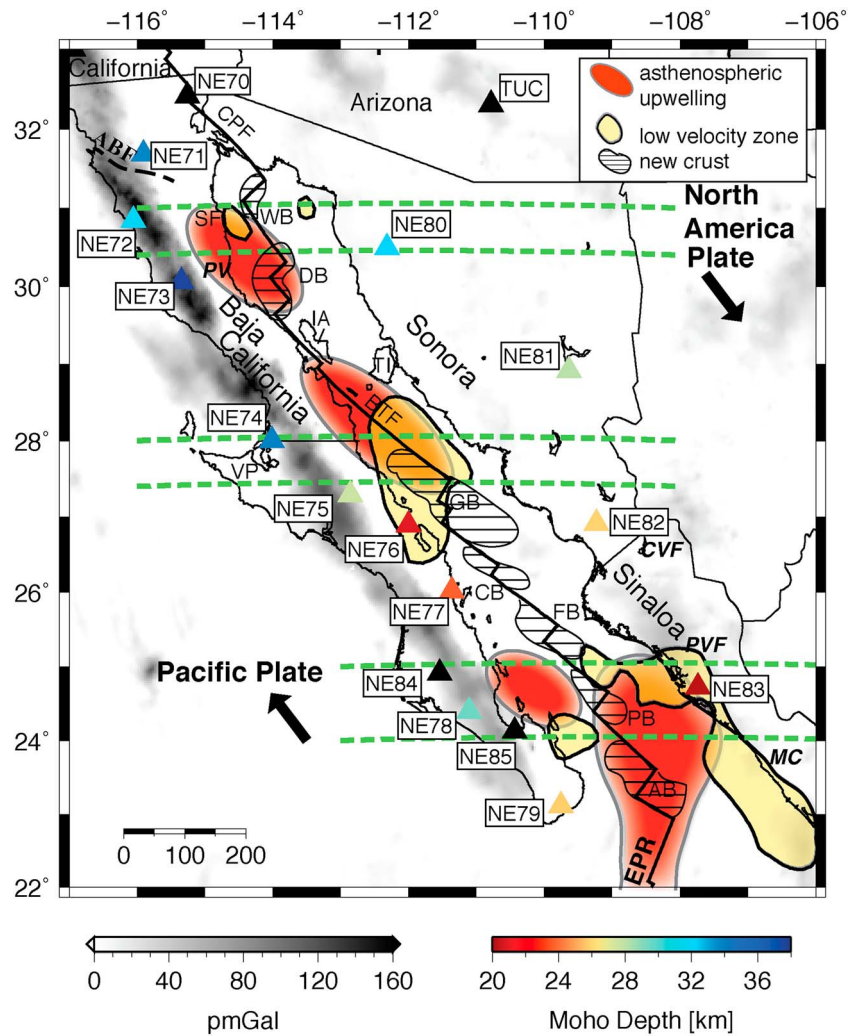


Figure 1. Tectonic setting of the Gulf of California. Triangles mark the NARS-Baja (NE) stations and TUC. Stations BOR, GOR, and DPP in California and UNM in Mexico lie outside the map region. Low-velocity zones are shaded yellow based on our 3.8 km/s contours of the shear wave velocities at 28–32 km depths. Asthenospheric upwellings [Di Luccio *et al.*, 2014] are shaded red. Horizontal black lines mark the approximate extent of new oceanic sedimentary or oceanic crust [Lizarralde *et al.*, 2007; Lonsdale, 1989; Martín-Barajas *et al.*, 2013]. Moho depths [Persaud *et al.*, 2007] are color coded at each station when available. The western (dark shading) and eastern (light shading) Peninsular Ranges batholith are shown with the magnetic potential grid [Langenheim and Jachens, 2003]. Green dashed lines are the shear wave profile locations shown in Figure 3; bottom two profiles extend to -105°E . Black arrows are plate motion vectors. AB = Alarcon Basin; ABF = Agua Blanca Fault; BTF = Ballenas Transform Fault; CB = Carmen Basin; CPF = Cerro Prieto Fault; CVF = Choix volcanic field; DB = Delfin Basin; EPR = East Pacific Rise; FB = Farallon Basin; GB = Guaymas Basin; IA = Isla Angel de la Guarda; MC = Mesa Cacaxtla shield volcano; PV = Puertecitos Volcanic Province; PVF = Pericos Volcanic Field; SF = San Felipe; TI = Isla Tiburón; VP = Vizcaino Peninsula; and WB = Wagner Basin.

overlying sediments also promoting excessive magmatism [Lizarralde *et al.*, 2007]. These authors also suggest that the northern Gulf is similar to the Guaymas Basin, a fact that has been recently challenged by Martín-Barajas *et al.* [2013]. Still, the overall picture of varying along-strike magmatic history and tectonic evolution in the rift basins is clear.

Notwithstanding the importance of mantle fertility, the three-dimensional processes of melt extraction likely controls along-strike crustal thickness variations and rift morphology. Here we investigate the mantle above the regions of active upwelling and below the new crust in the Gulf using regional surface wave tomography and provide new details on the spatial relationship of the rift basins and transform faults to underlying regions of partial melt. This study identifies a heterogeneous shear wave velocity structure beneath the Gulf

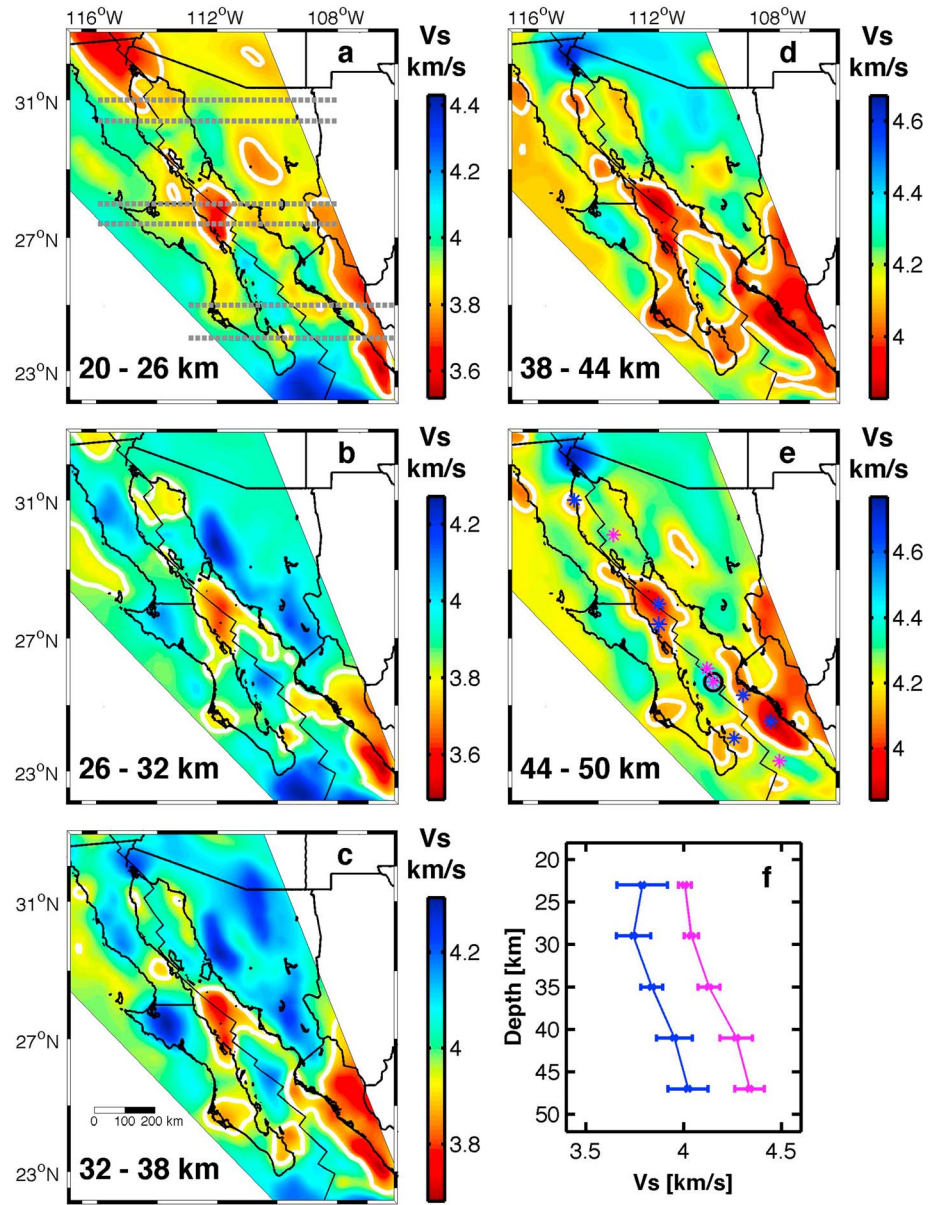


Figure 2. (a–e) Maps showing the average shear wave velocities in the depth range (labeled in the lower left corner of each map) of the uppermost mantle. Each map has a different color scale. White contours are velocities that are 6% lower than the depth average at the point marked by the black circle in Figure 2e. The contour values are (Figure 2a) 3.79 km/s; (Figure 2b) 3.83 km/s; (Figure 2c) 3.93 km/s; (Figure 2d) 4.08 km/s, and (e) 4.15 km/s. (f) Blue and pink lines show the average shear wave velocity profiles ± 1 standard deviation below the regions inside the LVZs (blue stars in Figure 2e) and below the regions outside the LVZs (pink stars in Figure 2e), respectively. The average velocities are significantly different at all depths. Dashed gray lines in Figure 2a are the profile locations shown in Figure 3. Figures 3e and 3f extend outside the map region.

and supports the concept that variations in the concentration of partial melt along strike of the rift axis play a fundamental role in the tectonomagmatic evolution of the plate boundary.

2. Data

We interpret the 10 km grid spacing 3-D shear wave velocity results derived by *Di Luccio et al.* [2014] in the 20–50 km depth range beneath the Gulf of California and the surrounding continental margins. Those authors used 76 events ($M=4.2\text{--}6.5$) that were recorded over a 5 year time period by the Network of Autonomously Recording Seismographs (NARS)-Baja array [Clayton et al., 2004], three Southern California Seismic Network

stations, the Geoscope station UNM in Mexico City, and the Global Seismographic Network station TUC in Tucson, Arizona (Figure 1). *Di Luccio et al.* [2014] computed the group velocity curves using the technique developed by *Herrmann* [1973]. These along path measurements were then converted into tomographic images using kernels which vary in off-path width as a function of the average velocity and of the period and using the least square algorithm from *Paige and Saunders* [1982] to smooth and damp the tomographic maps at different periods. We refer the reader to the work by *Di Luccio et al.* [2014] for details on the tomographic method.

In order to estimate the spatial resolution of the shear wave tomographic maps shown in Figure 2, we perform a checkerboard test for the study region at all periods, which is shown in Figure S1 in the supporting information. The results indicate that our tomographic inversion can predict the input model with very good resolution. In addition, we compute the sensitivity kernels at selected periods to support the fact that our results are well constrained in the 20–50 km depth range (Figure S1, bottom left). We further map the number of raypaths crossing each cell (Figure S1, bottom right), and the standard deviation recovered from the tomographic inversion of 25 bootstrap samples at 42 s period (Figure S2) to show that regions of higher resolution correspond to the denser number of ray paths, while the resolution is reduced in regions with a few crossing rays especially at shorter periods.

3. Shear Wave Velocity Results

The low-velocity zones (LVZs) are outlined in Figure 2 with constant velocity contours that change with each depth interval to indicate velocities that are 6% lower than the average beneath the point marked with the black circle in Figure 2e. This background velocity represents warm mantle due to its proximity to the plate boundary. Although this choice is arbitrary, a –6% lateral variation in shear wave speeds is significantly different (Figure 2f) and comparable to observed anomalies as low as –5% or –10% in the mantle beneath the Rio Grande Rift relative to the mantle beneath the Great Plains [*West et al.*, 2004] and –7% in the upper mantle beneath the Northern Basin and Range relative to the surrounding mantle there [*Ozalaybey et al.*, 1997].

In general, the broader LVZs are associated with the larger regions of asthenospheric upwelling (Figures 1 and 2). The LVZs are notably absent at most depths in the 20–38 km range on the northwestern Gulf margin near the Delfin Basin, north of Isla Angel de la Guarda, and in the northeastern Gulf margin north of Isla Tiburón (Figures 3b and 1 for locations). Except at 38–44 km depth (Figure 2d), LVZs are also conspicuously absent between ~24°N and ~26°N along the southeastern coast of the peninsula. This region is otherwise bounded to the north and south by LVZs that are present at all depths. In contrast, on the opposite side of the plate boundary, offshore Sinaloa and southern Sonora, LVZs are abundant and low shear wave velocities are observed at all depths.

We divide the LVZs into two groups, the shallower group extending from 20 to 38 km (Figures 2a–2c) and the deeper ones extending from 38 to 50 km (Figures 2d and 2e) based on their associated velocities and the possible interpretation of these features. The most prominent and continuous shallow group LVZs (yellow regions in Figure 1 based on shear wave velocities <3.8 km/s in the 28–32 km depth range) either overlie or are located close to regions of asthenospheric upwelling at 50–90 km depths as interpreted by *Di Luccio et al.* [2014] (shaded red in Figure 1). The LVZs in the shallow group show an increase in areal extent with increasing depth down to 32 km (Figures 2a and 2b). The most significant difference in this depth range is the disappearance of the LVZ near the continental Cerro Prieto Fault at the northern end of the Gulf (Figure 1 for location), which is replaced at 32–38 km with a velocity high. This feature continues to be a positive anomaly down to 50 km depth (Figures 2d and 2e).

To examine the vertical extent of the shallow group LVZs, we constructed profiles of our shear wave velocity model and associated these features with velocities of 3.6–3.8 km/s below 20 km depth that appear to merge from beneath the continent and extend into the Gulf (yellow contour fill beneath the Gulf in Figures 3a, 3c, 3d, 3e, and 3f). Although these features have velocities similar to the nearby continental margins at depths <20 km and appear to be connected to the crust there, as discussed in the next section, we interpret them to be either regions of partial melting or in the case of the northern Gulf as possibly being sourced from deeper continental crust as their velocities are within the range of warm lower continental crust. Though there are no constraints on the preextension lower crustal velocities for the Baja peninsula, V_5 is roughly

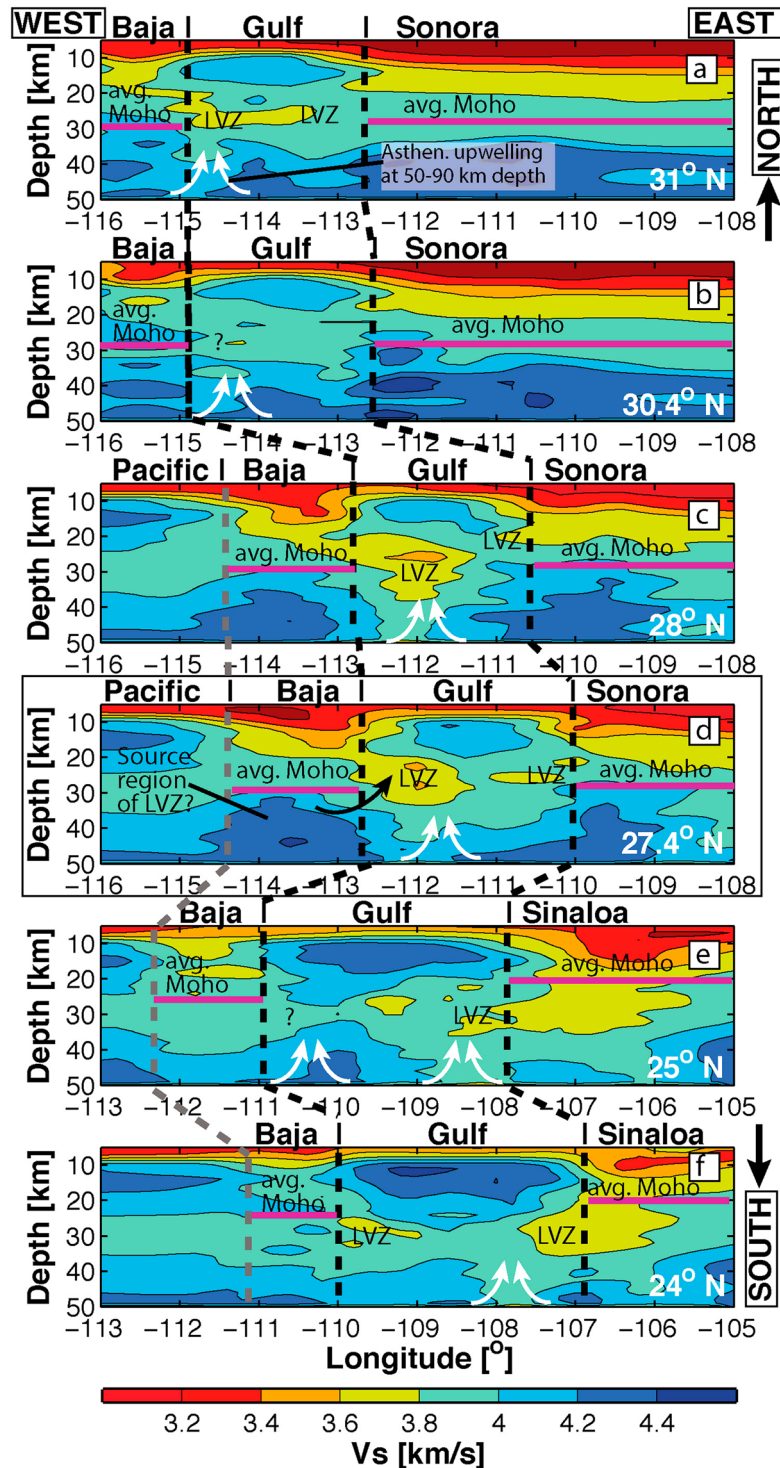


Figure 3. (a–f) Latitudinal profiles of shear wave velocities (average taken in and out of the plane over three grid points) are arranged north (top) to south (bottom), with their locations marked in the right lower corner of each profile and with dashed lines in Figures 1 (green) and 2a (gray). Figures 3e and 3f extend to -105°E outside those maps. Velocities are contoured every 0.2 km/s from 3.0 to 4.4 km/s with the LVZs indicated in yellow (3.6–3.8 km/s below 20 km). Labels above the profiles and dashed lines indicate provinces. White arrows mark regions with asthenospheric upwelling from *Di Luccio et al.* [2014]. Possible evidence of lower crustal flow from beneath Baja into the Gulf is observed in Figures 3a, 3c, and 3d, and marked with a black arrow in Figure 3d (see supporting information). Pink lines mark the average Moho depths based on receiver functions [Persaud et al., 2007] of 29.4 km in Baja California and 28.7 km in Sonora (Figures 3a–3d). In Figures 3e and 3f, average Moho depths beneath Baja are from NE78, NE79, and Lizarralde et al. [2007] and beneath Sinaloa from NE83.

4.0 km/s in the unextended core of the Sierra Madre Occidental of northern Mexico [Bonner and Herrin, 1999]. The range of observed low shear velocities (3.6–3.8 km/s in Figure 3) is on average 7% less than that of lower continental rift crust with $V_S \sim 3.98$ km/s (assuming $V_P = 7.12$ km/s [Christensen and Mooney, 1995] and average $V_P/V_S = 1.79$ [Persaud et al., 2007]). In addition, based on studies in the Northern Basin and Range [Ozalaybey et al., 1997, and references therein], these velocities are typical of continental crust there, and similar velocities are expected for the continental margins of the Gulf.

The LVZs in the deep group appear to decrease slightly in areal extent below 38 km depth (Figures 2d and 2e). They are most continuous along the Gulf margins particularly in the south central Gulf where they form a ring-like structure around the Carmen and Farallon Basins at depths below 38 km. They are only present along the Gulf axis in the southern part of the BTF merging into the Guaymas Basin, where they exist at all depths in both the shallow and deep groups (Figure 2) and in the Pescadero Basin near ~40 km depth (Figure 2d). In the northernmost Gulf near the Wagner Basin, the LVZ is noted at shallower depths (26–32 km, Figures 2b and 3a) compared to the deeper sections where they exist only in the Gulf margins.

4. Discussion and Conclusions

Based on their association with regions of upwelling, we interpret both the shallow and deep LVZs as representing partial melt or low-viscosity pockets embedded in a solid mantle matrix beneath the Gulf. Though mantle depletion is an important aspect of crustal accretion, a discussion of significant lateral variations in mantle depletion is not possible based on our results as melt depletion has a much smaller effect on density and therefore on seismic velocities than temperature [Schutt and Lesher, 2006]. It follows that our seismic velocity anomalies are likely indicative of compositional contrasts or thermal effects including partial melting and not the effect of melt extraction itself. Particularly, in the presence of high attenuation ($1/Q$), the influence of a small temperature difference on shear wave speeds is significant [Karato, 1993]. More specifically, where $Q \sim 100$, a –6% shear wave velocity anomaly reflects a –117°C temperature anomaly (assuming $\partial \ln V_S / \partial T = -1.54 \times 10^{-4} \text{ K}^{-1}$ [Karato, 1993]). The associated temperature anomaly is expected to be even smaller in the Gulf near the plate boundary, where $Q_S = 59$ at 1 Hz [Vidales-Basurto et al., 2014]. However, higher Q farther away from the plate boundary, where the LVZs are more frequently found rule out an interpretation of the LVZs based on temperature alone. Rather, this supports our interpretation of the LVZs as representing regions of concentrated partial melting in the uppermost mantle that is otherwise warm everywhere. A noted exception is near the BTF and Guaymas Basin where the LVZ is centrally located with respect to the plate boundary and likely reflect higher temperatures as well.

Typically, the crest of mid-ocean ridges are sites where magma from deep broad zones are focused into shallow areas as narrow as few kilometers by a process that depends on the viscous resistance to decompaction of the porous mantle matrix [Sparks and Parmentier, 1991]. The anastomosing geometry of the LVZs along with their wide spatial extent outside of the regions of deep mantle upwelling reflect the complexity of the mantle's structure at depths shallower than 50 km in the region where melt migration and extraction to shallow narrower regions should occur. With new oceanic or mixed oceanic sedimentary crust forming in all of the rift basins in the Gulf [Lizarralde et al., 2007; Martín-Barajas et al., 2013] (Figure 1) and seafloor spreading starting as early as ~3.5 Ma in the Alarcon Basin [Lonsdale, 1989], the occurrence of diffuse zones of partial melting in the mantle may explain the asynchronous timing in the transition to seafloor spreading. Below, we describe the along-strike differences in the LVZs with respect to the Gulf basins.

At depths of 26–50 km, the LVZ centered along the southern BTF (Figure 2) extends into the northern Guaymas Basin making it the only basin with magma supply at the ridge axis. This could mean that melt focusing is more effective at these depths beneath the Guaymas Basin, due to its proximity to the BTF, than under the other rift basins, thus making the Guaymas Basin magma rich at breakup [Lizarralde et al., 2007], and the Farallon, Pescadero, and Alarcon Basins magma poor. If our shear wave anomalies reflect the distribution of high concentrations of partial melt, which we assume has not changed significantly since the onset of rifting, ~6 Ma, we can confirm this interpretation based on the unique association of the northern Guaymas Basin with an LVZ. The notable exception is the Pescadero Basin, which also has an LVZ below 38 km depth (Figure 2d) and is well positioned near regions of partial melting. Hence, it should be more magmatic at breakup than the nearby Farallon and Alarcon Basins that have a widespread region of off-axis partial melting at 20–50 km depths. Off-axis magmatism has also been mapped up to ~50 km northwest and

~40 km southeast of the northern Guaymas Basin [Lizarralde *et al.*, 2011]. This is confirmed by our study since LVZs extend to large distances (>100 km) north of this basin and to shorter distances to the south (Figure 2d). These observations support our conclusion that on- or off-axis magma supply in combination with magmatic depletion of the mantle explains the differences in the magmatic history of these basins.

Additionally, recent (<1 Ma) basaltic volcanic fields in Sinaloa (Cacaxtla, Pericos, and Choix in Figure 1 [Ferrari *et al.*, 2013]) have an enriched geochemical signature (oceanic island basalt type). They represent melting of undepleted asthenosphere over a wide area, with a homogenous composition that has been maintained during the past 3.4 Myr [Ferrari *et al.*, 2013]. These volcanic fields could be fed by the LVZs in Figures 3e and 3f. Their young age along with their wide spatial extent fit our observations of off-axis regions of partial melting, however, their geochemical signature contrasts with the mid-oceanic ridge basalt-like signature of the nearby Alarcon Basin and East Pacific Rise (EPR) and may indicate complex geochemical variations between the LVZs.

Heating of the continental margins and the wide spatial extent of magmatism is further supported by thermochronology data onshore near the BTF that show a ~1.8 Ma heating event associated with magmatic leaking along the transform fault [Seiler *et al.*, 2009] (Figure 1). Since their study area had not migrated past the Delfin Basin, these authors proposed heating occurred during a very early stage of transform margin evolution. The most prominent and unchanging LVZ is located along the BTF. This anomaly extends from 20 to 50 km depth, above a deeper region of extensive mantle upwelling. The lack of deep rift basins associated with this feature is striking, and the similarity of this anomaly to the more restricted one at lower continental crust depths (20–26 km) near the Cerro Prieto Fault (Figure 2a) emphasizes the role of leaky transform fault zones in focusing magmatism.

Noteworthy is the lack of associated LVZs with the northern Gulf basins. A small LVZ is noted off axis and west of the Wagner Basin near San Felipe (Figure 1). Interestingly, the surface trace of the Agua Blanca Fault (ABF in Figure 1) aligns with this LVZ and the underlying region of asthenospheric upwelling. This LVZ is present at all depths and joins a larger LVZ between 26 and 32 km depth (Figure 2b). The LVZs in the northern Gulf are, however, smaller and the observed velocities (3.8–3.9 km/s) are not as low as elsewhere in the Gulf, though this pattern might be obscured by the overall lower velocities in the northern compared to the south central regions.

Next we examine an alternative mechanism for producing the shallow LVZs. The fact that the LVZs are more prevalent along the margins of the Gulf than along its axis points to the possible involvement of the continental margins in either focusing regions of partial melting or alternatively providing the source rocks for the LVZs, which would not require melting. For the latter interpretation, topographically driven lower crustal flow has been documented for the nearby Basin and Range [e.g., Kruse *et al.*, 1991] and presents a viable mechanism to drive lower crustal flow in the thickened crust of the Miocene Comondú volcanic arc that is thought to have existed at the site of the current Gulf. However, Ferrari *et al.* [2013] describe an earlier period of extension in the margins of the southern Gulf in the Late Oligocene (~29–24 Ma) with extension along the Sinaloa coast ending before ~11–10 Ma, and a considerable amount of crustal thinning (up to 100%) having occurred before that time. Extension in this region was ongoing in the Early Miocene (18–12 Ma) during the age of the supposed Comondú arc [Duque-Trujillo *et al.*, 2014]. This predates the commonly accepted ~12–6 Ma period of minor extension and contradicts the traditional view of a well-developed arc existing at ~6 Ma, instead a zone of extended crust occupied the site of the future southern Gulf [Bryan *et al.*, 2013]. If lower crustal flow occurred here, it likely occurred before 6 Ma, and unless the crust was very weak and flow continued offshore at breakup [e.g., Clift *et al.*, 2002], little evidence might be found beneath the Gulf. In addition, the Moho topography in seismic profiles across the south central rift basins including the Guaymas Basin [Lizarralde *et al.*, 2007] does not support lower crustal flow for those rift segments.

No similar history of significant pre-12 Ma extension has been documented for the Gulf north of the Guaymas Basin. In contrast, the oldest synrift sequence (6.4–5.8 Ma) in the Puertecitos Volcanic Province (PV in Figure 1) overlies middle Miocene (20–16 Ma) andesites of the volcanic arc, which formed during the final stages of subduction thus recording the transition from subduction to rifting [Martin-Barajas *et al.*, 1995]. In the Wagner Basin, the mismatch between fault slip rates and subsidence supports lower crustal flow there [Contreras-Pérez *et al.*, 2012]. Evidence for lower crustal flow in the northern Gulf is based on the fact that crustal thickness variations are smoothed out relative to the strong thickness variations of the lower crust [Gonzalez-Fernandez *et al.*, 2005] and is supported by the eastward thinning of the Baja peninsula

crust [Lewis *et al.*, 2001; Persaud *et al.*, 2007]. Approximately, 10% of the excess lower crust in the northern Gulf is estimated to have come from beneath Baja with the other 90% derived from Sonora [Martin-Barajas *et al.*, 2013]. In that study, the regions of excess crust are shallower than 20 km except for a small area north of Isla Tiburón, which lies outside the resolution of our study. Considering these factors, our discussion below is limited to the Gulf north of the Guaymas Basin and provides an alternative interpretation of the shallow LVZs in that region as possibly being solid low-viscosity lower continental crust instead of regions of partial melting.

Assuming that the crust in the continental margins north of the Guaymas Basin (Figures 3a, 3c, and 3d) was thickened prior to the start of extension, the addition of a heat source to further soften the crust could initiate a change from no-flow to flow conditions [Bertotti *et al.*, 2000]. The association between the LVZs and asthenospheric upwellings suggests lateral flow was assisted by the heat source and not solely topographically driven. The shallow group LVZs are laterally continuous and pronounced down to depths of 32–38 km (Figure 2c) and continue in cross section down to ~40 km (e.g., Figure 3c). If sourced from the nearby continental margins, the initial prerift crustal thickness should have been close to 40 km. On average, the current Baja peninsula crust is ~30 km thick, with the maximum crustal thickness from receiver functions of 37.5 km beneath NE73 [Persaud *et al.*, 2007] located in the western Peninsular Ranges batholith (PRB), which has undergone less brittle extension relative to the eastern PRB (Figure 1). We estimate (see the supporting information) the amount of additional crust needed beneath the Baja peninsula to produce the LVZ shown in Figure 3d to be ~10 km beneath the western PRB. This requires an ~37.6 km prerift crustal thickness beneath Baja in that cross section in agreement with the deepest depth reached by the shallow LVZs. The LVZs nearest the continental margins of the Gulf also seem to pond at around ~30 km depth (Figures 3a and 3c). This suggests that the LVZs are more recently produced from crust that is ~30 km thick, close to the current average crustal thicknesses in Baja of 29.4 km based on receiver functions at widely spaced stations in Figure 1 [Persaud *et al.*, 2007] and greater than the minimum for lower crustal flow of 20 to 25 km [e.g., McKenzie *et al.*, 2000].

There are many factors that could influence our first-order estimate. First, we do not take rift-parallel flow or flow into the base of the new crust or shallower than 20 km into account. Also, some portions of the lower continental crust might have been removed to produce the unique suite of adakitic rocks found in Baja through thermal erosion and melting if these were formed by the melting of lower mafic arc crust as proposed by Castillo [2008] rather than from slab melting [Calmus *et al.*, 2011]. Future studies in this region will provide further constraints on the LVZs and possibly refine our interpretation. To first order, our estimate leaves open buoyancy-driven lower crustal flow assisted by a mantle heat source as mechanism for producing some of the shallow LVZs in the northern Gulf. Major findings include a heterogeneous shear wave velocity structure beneath the Gulf and significant along axis variations in the distribution of partial melt.

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